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Measurement of the CP-violating Asymmetries in $B^0 \to K^0_S \pi^0$ and of the Branching Fraction of $B^0 \to K^0 \pi^0$

The *BABAR* Collaboration

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Abstract

We present a measurement of the time-dependent CP-violating asymmetries in $B^0 \to K^0_S\pi^0$ decays based on 348 million $\Upsilon(4S) \to B\overline{B}$ events collected by the *BABAR* experiment at the PEP-II asymmetric-energy B Factory at SLAC. We measure the direct CP-violating asymmetry $C_{K^0_S\pi^0} = 0.20 \pm 0.16 \pm 0.03$ and the CP-violating asymmetry in the interference between mixing and decay $S_{K^0_S\pi^0} = 0.33 \pm 0.26 \pm 0.04$ where the first error is statistical and the second systematic. On the same sample, we measure the decay branching fraction, obtaining $\mathcal{B}(B^0 \to K^0_S\pi^0) = (10.5 \pm 0.7 \pm 0.5) \times 10^{-6}$. All results presented here are preliminary.

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The recent measurements of the weak phase β in $b \to c\bar{c}s$ decays from *BABAR* [1] and Belle [2], have reached the precision of the prediction from fits of the unitarity triangle [3], obtained combining the information from *CP*-conserving quantities to the measurements of other *CP*-violating (CPV) processes. The agreement between the two determinations has shown that the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [4] correctly describes the source of effects in the Standard Model (SM).

With *BABAR* and Belle collecting more data, one of the major goals of the two experiments is to search for indirect evidence of new physics (NP). One possible strategy consists in comparing the established value of β to independent determinations of the same quantity, obtained from penguin-dominated (in SM) $b \to s\bar{q}q$ ($q = \{d, s\}$) decays [5, 6]. [5]

In the SM, the parameters C_f (describing the direct CPV asymmetry) and S_f (describing the CPV asymmetry in the interference between mixing and decay) are expected to be consistent with the values from $b \to c\bar{c}s$ decays (namely $C_f \sim 0$ and $S_f \sim \sin 2\beta$). Small deviations from this expectation can be induced by additional CKM suppressed contributions to the amplitude. On the other hand, additional radiative loop contributions from NP processes may produce large deviations.

In this letter we present updated measurements of the time-dependent CPV asymmetries and branching fraction of the decay $B^0 \to K^0\pi^0$. The CKM and color suppression of the tree-level $b \to s\bar{u}u$ transition leads to the expectation that this decay is dominated by a top quark mediated $b \to s\bar{d}d$ penguin diagram, which carries a weak phase $\arg(V_{tb}V_{ts}^*)$. If non-leading contributions are ignored, the time-dependent CPV asymmetry is governed by $\sin 2\beta$.

The results presented here are based on 348 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II e^+e^- collider, located at the Stanford Linear Accelerator Center. The *BABAR* detector, which is described in [7], provides charged particle tracking through a combination of a five-layer double-sided silicon micro-strip detector (SVT) and a 40-layer central drift chamber (DCH), both operating in a 1.5 T magnetic field to provide momentum measurements. Charged kaon and pion identification is achieved through measurements of particle energy loss (dE/dx) in the tracking system and Cherenkov cone angle (θ_c) in a detector of internally reflected Cherenkov light (DIRC). A segmented CsI(Tl) electromagnetic calorimeter (EMC) provides photon detection and electron identification. Finally, the instrumented flux return (IFR) of the magnet allows discrimination between muons and pions.

We reconstruct $K_S^0 \to \pi^+\pi^-$ candidates from pairs of oppositely charged tracks. The two-track combinations must form a vertex with $\pi^+\pi^-$ invariant mass within 11.2 MeV/c^2 (3.5σ) of the etsablished K_S^0 mass [8] and reconstructed proper lifetime greater than five times its uncertainty. We form $\pi^0 \to \gamma\gamma$ candidates from pairs of photon candidates in the EMC that are isolated from any charged tracks, carry a minimum energy of 50 MeV, fall within the mass window $110 < m_{\gamma\gamma} <$ 160 MeV/c^2, and produce the expected lateral shower shapes. Finally, we construct $B^0 \to K_S^0\pi^0$ candidates by combining K_S^0 and π^0 candidates in the event. For each B candidate two nearly independent kinematic variables are computed. The first one is m_B, the invariant mass of the reconstructed B meson, $B_{\rm rec}$. The second one is $m_{\rm miss}$, the invariant mass of the other B, $B_{\rm tag}$, computed from the known beam energy, applying a mass constraint to $B_{\rm rec}$. For signal decays, the two variables peak near the B^0 mass with a resolution of ~ 5.5 MeV/c^2 (~ 31 MeV/c^2) for $m_{\rm miss}$ (m_B). Both the $m_{\rm miss}$ and m_B distributions exhibit a low-side tail from leakage of energy deposits out of the EMC. We select candidates within the window $5.11 < m_{\rm miss} < 5.31$ GeV/c^2 and $5.1294 < m_B < 5.4294$ GeV/c^2, which includes the signal peak and a "sideband" region for

[5] Unless explicitly stated, conjugate decay modes are assumed throughout this paper.

background characterization. For the 0.8 % of events with more than one candidate, we select the combination with the smallest $\chi^2 = \sum_{i=\pi^0,K^0_S}(m_i - m'_i)^2/\sigma^2_{m_i}$, where m_i (m'_i) is the measured (etablished) mass and σ_{m_i} is the estimated uncertainty on the measured mass of particle i.

The sample of $B^0 \to K^0_S\pi^0$ candidates is dominated by random $K^0_S\pi^0$ combinations from $e^+e^- \to q\overline{q}$ ($q = \{u,d,s,c\}$) fragmentation. Using large samples of simulated $B\overline{B}$ events, we find that backgrounds from other B meson decays can be neglected. We exploit topological observables to discriminate the jet-like $e^+e^- \to q\overline{q}$ events from the more uniformly distributed $B\overline{B}$ events. We compute the value of L_2/L_0, where $L_j \equiv \sum_i |\mathbf{p}^*_i||\cos\theta^*_i|^j$. Here, $\mathbf{p}^*_i$ is the momentum of particle i in the $\Upsilon(4S)$ rest frame and θ^*_i is the angle between $\mathbf{p}^*_i$ and the sphericity axis [9] of the B^0 candidate, and the sum does not include the decay tree of the reconstructed B. In order to reduce the number of background events, we require $L_2/L_0 < 0.55$. We also use the distribution of this ratio to discriminate the signal from the residual background. Using a full detector simulation, we estimate that our selection retains $(34.3 \pm 1.3)\%$ of the signal events. Here, the error includes statistical and systematic contributions. The systematic contribution is dominated by the reconstruction of K^0_S and π^0.

For each $B^0 \to K^0_S\pi^0$ candidate, we examine the remaining tracks and neutral candidates in the event to determine if the $B_{\rm tag}$ meson decayed as a B^0 or a $\overline{B}^0$ (flavor tag). We use a neural network (NN) to determine the flavor of the $B_{\rm tag}$ meson from kinematic and particle identification information [10]. Each event is assigned to one of seven mutually exclusive tagging categories, designed to combine flavor tags with similar performance and vertex resolution. We parameterize the performance of this algorithm in a data sample ($B_{\rm flav}$) of fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$ decays. The average effective tagging efficiency obtained from this sample is $Q = \sum_c \epsilon^c_S(1-2w^c)^2 = (30.4 \pm 0.3)\%$, where ϵ^c_S and w^c are the efficiencies and mistag probabilities, respectively, for events tagged in category c. We take into account differences in tagging efficiency (for signal and background) and mistag (only for signal) for B^0 and $\overline{B}^0$ events, in order to exclude any source of fake CPV effects. For the background, the fraction of events (ϵ^c_B) and the asymmetry in the rate of B^0 versus $\overline{B}^0$ tags in each tagging category are extracted from the fit to the data.

Time-dependent CPV asymmetries are determined by reconstructing the distribution of the difference of the proper decay times, $\Delta t \equiv t_{CP} - t_{\rm tag}$, where the t_{CP} refers to the signal B^0 and $t_{\rm tag}$ to the $B_{\rm tag}$. At the $\Upsilon(4S)$ resonance, the Δt distribution follows

$$\mathcal{P}^{B^0}_{\overline{B}^0}(\Delta t) \;=\; \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [\, 1 \;\pm\; (\; S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)\,)\,] \;, \qquad (1)$$

where the upper (lower) sign corresponds to $B_{\rm tag}$ decaying as B^0 ($\overline{B}^0$), τ is the B^0 lifetime averaged over the two mass eigenstates, Δm_d is the mixing frequency, C_f is the magnitude of direct CP violation in the decay to final state f, and S_f is the magnitude of CP violation in the interference between mixing and decay. For the case of pure penguin dominance, we expect $S_{K^0_S\pi^0} = \sin 2\beta$, and $C_{K^0_S\pi^0} = 0$.

We compute the proper time difference Δt from the known boost of the e^+e^- system and the measured $\Delta z = z_{CP} - z_{\rm tag}$, the difference of the reconstructed decay vertex positions of the $B^0 \to K^0_S\pi^0$ and $B_{\rm tag}$ candidate along the boost direction (z). A description of the inclusive reconstruction of the $B_{\rm tag}$ vertex is given in [11]. For the $B^0 \to K^0_S\pi^0$ decay, where no charged particles are present at the decay vertex, we identify the vertex of the fully reconstructed B using the single K^0_S trajectory from the $\pi^+\pi^-$ momenta and the knowledge of the average interaction point (IP), which is determined on a run-by-run basis from the spatial distribution of vertices from

two-track events. We compute Δt and its uncertainty from a geometric fit to the $\Upsilon(4S) \to B^0\overline{B}^0$ system that takes this IP constraint into account. We further improve the sensitivity to Δt by constraining the sum of the two B decay times $(t_{CP} + t_{\rm tag})$ to be equal to $2\,\tau$ with an uncertainty $\sqrt{2}\,\tau_{B^0}$, which effectively constrains the two vertices to be near the $\Upsilon(4S)$ line of flight. We have verified in a Monte Carlo simulation that this procedure provides an unbiased estimate of Δt.

The per-event estimate of the uncertainty on Δt reflects the strong dependence of the Δt resolution on the K^0_S flight direction and on the number of SVT layers traversed by the K^0_S decay daughters. In about 60 % of the events, both pion tracks are reconstructed from at least 4 SVT hits, leading to sufficient resolution for the time-dependent measurement. The average Δt resolution in these events is about 1.0 ps. For events which fail this criterion or for which $\sigma_{\Delta t} > 2.5\,$ps or $\Delta t > 20\,$ps, the Δt information is not used. However, since C_f can also be extracted from flavor tagging information alone, these events still contribute to the measurement of C_f and the signal yield.

We obtain the probability density function (PDF) for the time-dependence of signal decays from the convolution of Eq. 1 with a resolution function $\mathcal{R}(\delta t \equiv \Delta t - \Delta t_{\rm true}, \sigma_{\Delta t})$, where $\Delta t_{\rm true}$ is the true value of Δt. The resolution function is parameterized as the sum of a 'core' and a 'tail' Gaussian, each with a width and mean proportional to the reconstructed $\sigma_{\Delta t}$, and a third Gaussian centered at zero with a fixed width of 8 ps [11]. We have verified in simulation that the parameters of $\mathcal{R}(\delta t, \sigma_{\Delta t})$ for $B^0 \to K^0_S\pi^0$ decays are similar to those obtained from the $B_{\rm flav}$ sample, even though the distributions of $\sigma_{\Delta t}$ differ considerably. Therefore, we extract these parameters from a fit to the $B_{\rm flav}$ sample. We find that the Δt distribution of background candidates is well described by a δ function convolved with a resolution function with the same functional form as used for signal events. The parameters of the background function are determined together with the CPV parameters and the signal yield.

We extract the CPV parameters from an extended unbinned maximum-likelihood (ML) fit to kinematic, event shape, flavor tag, and time structure variables. We construct the likelihood from the product of one-dimensional PDFs, since all the linear correlations are negligible. The systematic from residual correlations is taken into account, as explained below.

The PDFs for signal events are parameterized from either a largest sample of fully-reconstructed B decays in data or from simulated events. For background PDFs, we select the functional form from data in the sideband regions, included in the fitted sample, of the other observables where backgrounds dominate

The likelihood function is defined as:

$$\begin{aligned}\mathcal{L}(S_f, C_f, N_S, N_B, f_S, f_B, \vec{\alpha}) = \frac{e^{-(N_S+N_B)}}{(N_S+N_B)\,!} \times \prod_{i \in \mathrm{w}/\,\Delta t} \left[N_S f_S \epsilon^c_S \mathcal{P}_S(\vec{x}_i, \vec{y}_i; S_f, C_f) + N_B f_B \epsilon^c_B \mathcal{P}_B(\vec{x}_i, \vec{y}_i; \vec{\alpha})\right] \times \\ \prod_{i \in \mathrm{w/o}\,\Delta t} \left[N_S(1-f_S)\epsilon^c_S \mathcal{P}'_S(\vec{x}_i; C_f) + N_B(1-f_B)\epsilon^c_B \mathcal{P}'_B(\vec{x}_i; \vec{\alpha})\right],\end{aligned}$$

where f_S is the fraction of events with Δt information (w/ Δt) and f_B is the fraction of events without it (w/o Δt).

The probabilities $\mathcal{P}_S$ and $\mathcal{P}_B$ are products of PDFs for signal (S) and background (B) hypotheses evaluated for the measurements $\vec{x}_i = \{m_B, m_{\rm miss}, L_2/L_0, \cos\theta^*_B, \mathrm{tag}, \mathrm{tagging\ category}\}$ and $\vec{y}_i = \{\Delta t, \sigma_{\Delta t}\}$. In the formula, $\vec{\alpha}$ represents the set of parameters that define the shape of the PDFs. Along with the CPV asymmetries S_f and C_f, the fit extracts the yields N_S and N_B, the fraction of events with Δt information f_S and f_B, and the parameters $\vec{\alpha}$ which describe the background PDFs.

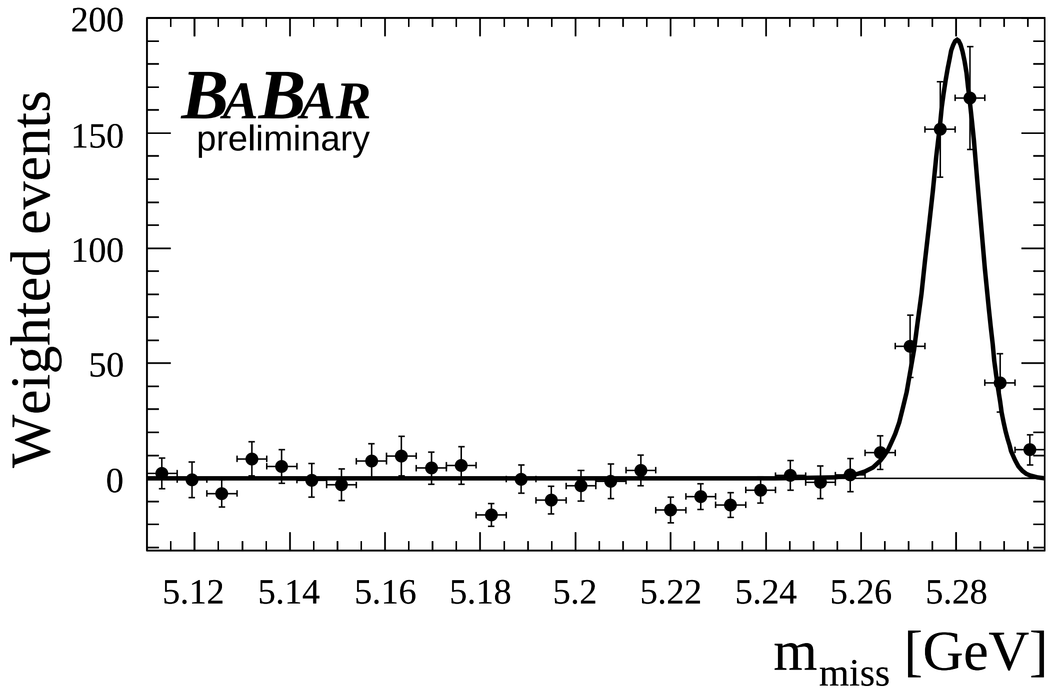

Figure 1: m_{miss} distribution for signal events on data (dots), obtained using the sPlot technique [12] to subtract background events. The solid curve represents the shape of signal PDF, as obtained from the fit.

Fitting the data sample of 17058 $B^0 \to K^0_S\pi^0$ candidates, we find $N_S = 425 \pm 28$ signal decays with $S_{K^0_S\pi^0} = 0.33 \pm 0.26 \pm 0.04$ and $C_{K^0_S\pi^0} = 0.20 \pm 0.16 \pm 0.03$, where the uncertainties are statistical and systematic respectively. Taking into account the selection efficiency and the number of $B\overline{B}$ pairs included in the fitted data sample, we also obtain $\mathcal{B}(K^0\pi^0) = (10.5 \pm 0.7 \pm 0.5) \times 10^{-6}$.

Figure 1 shows the m_{miss} distributions for signal events, where background is subtracted using the sPlot technique [12]. Figure 2 shows distributions of Δt for B^0- and $\overline{B}^0$-tagged events, and the asymmetry $\mathcal{A}_{K^0_S\pi^0}(\Delta t) = \left[N_{B^0} - N_{\overline{B}^0}\right] / \left[N_{B^0} + N_{\overline{B}^0}\right]$ as a function of Δt, also obtained with the sPlot event weighting technique. N_B^0 ($N_{\overline{B}^0}$) represents the number of events tagged as B^0 ($\overline{B}^0$).

In order to investigate possible biases introduced in the CPV measurements by the IP-constrained vertexing technique, we examine $B^0 \to J/\psi\, K^0_S$ decays in data, where $J/\psi \to \mu^+\mu^-$ or $J/\psi \to e^+e^-$. In these events we determine Δt in two ways: by fully reconstructing the B^0 decay vertex using the trajectories of charged daughters of the J/ψ and the K^0_S mesons, or by neglecting the J/ψ contribution to the decay vertex and using the IP constraint and the K^0_S trajectory only. This study shows that within statistical uncertainties, the IP-constrained Δt measurement is unbiased with respect to the standard technique and that the obtained values of $S_{J/\psi\, K^0_S}$ and $C_{J/\psi\, K^0_S}$ are consistent.

To compute the systematic error associated with the signal yield and CPV parameters, each of the input parameters to the likelihood fit is shifted by $\pm 1\sigma$ from its nominal value and the fit is repeated. Here, $\pm 1\sigma$ is the associated error, as obtained from the B_{flav} sample (for Δt and

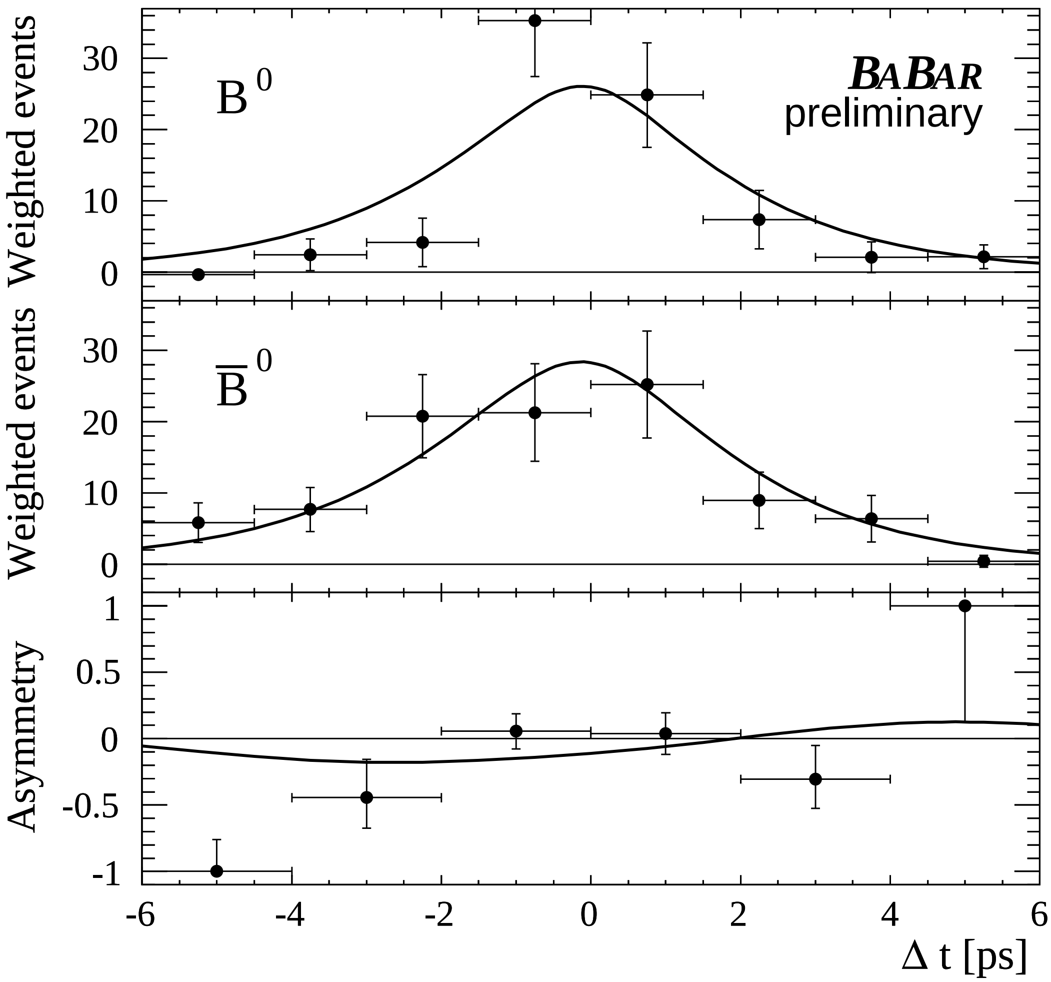

Figure 2: Distributions of Δt for events weighted with the sPlot technique for B_{tag} tagged as (a) B^0 or (b) $\overline{B}^0$, and (c) the asymmetry $\mathcal{A}(\Delta t)$. The points are weighted data and the curves are the PDF projections.

tagging) or from Monte Carlo. This contribution to the systematic error takes into account the limited statistics we used to parameterize the shape of the likelihood. We obtain a systematic error of 0.72 events on the yield, and of 0.006 (0.010) on $S_{K^0_S\pi^0}$ ($C_{K^0_S\pi^0}$). As an additional systematic error associated with the shape of the PDF, we also quote the largest deviation observed when the individual signal PDFs are floated in the fit. This gives a systematic error of 11 events on the yield, and of 0.007 (0.021) on $S_{K^0_S\pi^0}$ ($C_{K^0_S\pi^0}$). The output values of the PDF parameters are also used to associate a systematic error to the selection cuts on the likelihood variables. We evaluate the systematic error coming from the neglected correlations among fit variables using a set of toy Monte Carlo experiments, in which we embed signal events from full detector simulations. We use the average shift in yield (2.3 events) and CPV parameters (0.003 on $S_{K^0_S\pi^0}$ and 0.015 on $C_{K^0_S\pi^0}$) as the associated uncertainty. We estimate the background from other B decays to be negligible in the nominal fit. We take into account a systematic error induced on signal yield and CPV parameters by this neglected component, embedding B background events in the dataset and evaluating the average shift in the fit result: 4.5 events on the signal yield, 0.003 on $S_{K^0_S\pi^0}$ and 0.002 on $C_{K^0_S\pi^0}$.

For CPV parameters, we evaluate the additional systematic uncertainty related to the fit method using the largest difference between the fitted and generated values of $S_{K^0_S\pi^0}$ (0.027) and $C_{K^0_S\pi^0}$ (0.003). To quantify possible additional systematic effects, we examine large samples of simulated $B^0 \to K^0_S\pi^0$ and $B^0 \to J/\psi K^0_S$ decays. We employ the difference in resolution function parameters extracted from these samples to evaluate uncertainties due to the use of the resolution function $\mathcal{R}$ extracted from the $B_{\rm flav}$ sample. We assign a systematic uncertainty of 0.01 on $S_{K^0_S\pi^0}$ and 0.02 on $C_{K^0_S\pi^0}$ due to the uncertainty in $\mathcal{R}$. We include a systematic uncertainty of 0.002 on $S_{K^0_S\pi^0}$ and 0.001 on $C_{K^0_S\pi^0}$ to account for a possible misalignment of the SVT. We consider large variations of the IP position and resolution, which produce a systematic uncertainty of 0.004 on $S_{K^0_S\pi^0}$ and 0.001 on $C_{K^0_S\pi^0}$. Additional contributions come from the error on the known B^0 lifetime (0.0022 on both $S_{K^0_S\pi^0}$ and $C_{K^0_S\pi^0}$), the value of Δm_d (0.0017 on both $S_{K^0_S\pi^0}$ and $C_{K^0_S\pi^0}$), and the effect of interference on the tag side (0.0014 on $S_{K^0_S\pi^0}$ and 0.014 on $C_{K^0_S\pi^0}$).

For the branching fraction, systematic errors come from the knowledge of selection efficiency, $(34.3 \pm 1.3)\%$, the counting of $B\overline{B}$ pairs in the data sample, $(347.5 \pm 1.9) \times 10^6$ $B\overline{B}$ pairs, and the branching fractions of the B decay chain ($\mathcal{B}(K^0_S \to \pi^+\pi^-) = 0.6895 \pm 0.0014$ and $\mathcal{B}(\pi^0 \to \gamma\gamma) = 0.9880 \pm 0.0003$). [8]

In summary, we have performed a measurement of the time-dependent CPV asymmetries of $B^0 \to K^0_S\pi^0$ and the branching fraction of $B^0 \to K^0\pi^0$. We measured the parameters of CPV asymmetry $C_{K^0_S\pi^0} = 0.20 \pm 0.16 \pm 0.03$ and $S_{K^0_S\pi^0} = 0.33 \pm 0.26 \pm 0.04$, and the branching fraction $\mathcal{B}(B^0 \to K^0\pi^0) = (10.5 \pm 0.7 \pm 0.5) \times 10^{-6}$. The first error is statistical and the second systematic. All the results presented here are preliminary.

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